

# An Anomalous UV Extension in NGC6251<sup>1</sup>

P. Crane and J. Vernet

European Southern Observatory, Karl-Schwarzschild Strasse 2, D-85748 Garching,  
Germany.

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## ABSTRACT

Deep U-band FOC images of the nuclear region of NGC6251 have revealed a region of extended emission which is most probably radiation scattered from a continuum source in the nucleus. This radiation lies interior to a dust ring, is nearly perpendicular to the radio jet axis, and is seen primarily in the FOC U and b filters. The extension has a low observed polarization( $\leq 10\%$ ), and is unlikely to arise from line emission. We know of no other examples similar to what we have found in NGC 6251, and we offer some tentative explanations. The nuclear morphology shows clear similarities to that seen in the nucleus of NGC 4261 except for the extended U-band radiation.

*Subject headings:* polarization; radiation mechanisms: non-thermal; galaxies: individual (NGC6251); galaxies: jets; ultraviolet: galaxies

## 1. Introduction

Until the HST data were available, the optical images of NGC 6251 showed a rather normal elliptical galaxy although the presence of dust in the nuclear regions had been reported(Nieto *et al.*,1983). This dust was shown to be confined to a ring or disk like structure by HST(O’Neil *et al.*,1994). Thus NGC6251 was and is thought to be merely another case in which the dust features delineate the morphology and possibly the dynamics of the nuclear regions of a galaxy which is otherwise unremarkable in the optical.

NGC6251 is classified as E2, lies at a distance of 114 Mpc ( $v = 7400 \text{ km/s}$   $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ) and has an absolute magnitude of  $M_v = -21.3$ . Optical spectra(Shuder, and Osterbrock,1981 ; Antonucci,1984) show low level Seyfert activity if any at all. The Seyfert classification has probably been prejudiced by the rather spectacular appearance of this galaxy in the radio. Indeed, the radio images(Perley, Bridle, and Willis, 1984) reveal a highly collimated jet that extends to at least 1 Mpc and shows structure on every scale that it has been observed(Jones and Wehrle, 1994). The X-ray data(Birkinshaw and Worrall,1993) show evidence for an unresolved( $\leq 3''$ ) non-thermal nuclear component in the core. Optical emission associated with one of the bright radio knots has been detected about 20 arcsecs from the nucleus (Keel, 1988).

NGC 6251 was observed with the FOC on HST as part of a survey of “normal” elliptical galaxies(Crane *et al.*, 1993a). Important for the results reported here, this survey is so-far the only one with HST which includes two colors one of which is in the near UV. The initial images were taken before the first repair mission and suffered severely from the spherical aberration. Nevertheless, it was noticed that the UV(F342W) image and only this image showed an unexpected extension that did not seem to be an artifact related to the point spread function(Crane, 1993). Subsequent pre-Costar images also revealed the same extension(Crane, 1996). Motivated by this anomaly, a set of post-Costar images was

obtained that clearly revealed the remarkable U-band emission inside the dust ring in NGC 6251 that is reported here.

## 2. Data and Analysis

The data come from our own FOC observations and from PC2 images available in the HST archive. Table 1 summarizes the observational material. Figure 1 shows a composite of the FOC and PC2 images and clearly demonstrates the main discovery reported here; the emission extending to the south of the nucleus and which is seen so prominently in the F342W image. The presence of the U-band emission is particularly remarkable considering its apparent absence in the PC2 V and I images and it's weakness in the F410M image. The anomalous emission is confined to the region interior to the dust ring. It extends about 0.5 arcsec or 280 pc from the nucleus. The slight extension seen to the North of the nucleus appears to be cut-off by the dust ring. This is particularly clear when the U and V images are compared in detail (see Fig. 2). Thus we suggest that the emission fills the inner regions of the dust ring and is consequently not intrinsically asymmetric; the details of what we observe are determined by the orientation and morphology of the dust ring. To be precise, the dust ring does not lie in a plane, but is bent on the NE side of the nucleus, and thus obscures the emission more effectively. as can be seen in Fig. 2. However, we cannot rule out some clumping or patchy obscuration in the emission.

The FOC images contain interesting details of structure within about 20–40 pc of the nucleus. Also, there is some evidence for radiation emerging close to the radio axis, but this is very faint. We will discuss these in a subsequent communication(Vernet, and Crane, 1997).

After the clear detection of the extended U-band emission in the nucleus, FOC

polarization images were obtained since one potential explanation for the extended emission was scattering of photons from a hot central source. The polarization data were processed following the same procedures used for the Pictor A data(Thomson, Crane, and MacKay, 1995). Figure 3 shows the resulting polarization map. The low polarization in the extension and the apparent lack of change along the extension imply that, if the emission is due to scattered photons, the scattering process must somehow produce a low polarization. We put an upper limit of  $\leq 10\%$  on the polarization in the extended emission. By analyzing the the fractional polarization statistical distribution in the SW extension, we determine an average polarization of about 5% but with a big uncertainty. We note that regions closer to the nucleus do show enhanced polarization as would be expected if the radiation is scattered. We also note a small region of enhanced brightness and polarization to the east of the nucleus in the direction of the radio counter-jet reported by Jones, *et al.*, 1986.

In order to further explore the origin of this emission, we have performed simple photometry by extracting an intensity profile 0.1 arcsec wide along the axis of the emission feature in each of the four bands available. Figure 4 shows these extracted profiles. We note that the observed flux is very similar in both the F410M and F342W traces, although the F410M trace is considerably more noisy. The total fluxes in the extension are  $2.1 \pm 0.5$  and  $1.5 \pm 0.5 \times 10^{-18}$  ergs s $^{-1}$  cm $^{-2}$  Å $^{-1}$  for at 3400Å and 4100Å respectively. These fluxes were determined in a 0.1 arcsec wide region extending from 0.15 to 0.5 arcsec from the nucleus. These may be compared to estimated fluxes from the unresolved nucleus of  $\mathcal{F}(4100) \geq 1.0 \times 10^{-16}$  and  $\mathcal{F}(3400) \geq 7.3 \times 10^{-17}$  ergs s $^{-1}$  cm $^{-2}$  Å $^{-1}$ . These are lower limits because we have not corrected for the unknown non-linearities in the FOC which may be as large as 10%. For the nucleus in the V and R bands, we find fluxes of  $\mathcal{F}(5550) = 1.0 \times 10^{-16}$  and  $\mathcal{F}(8140) = 8.6 \times 10^{-17}$  ergs s $^{-1}$  cm $^{-2}$  Å $^{-1}$ . For the V, or F555 image, this corresponds to  $V = 18.9$ .

The details of the profiles in Fig. 4 led us to question whether or not the extension could be seen in the V band image. Indeed, a careful inspection of the V-I color map shows some evidence that the extension is also present in the V-band image. We determined an upper limit for the extended emission in the F555W band of roughly half the flux seen in the F410M and F342W images.

In order to deredden these data, we have used a standard galactic extinction law. Shuder and Osterbrock(1981) report  $E(B - V) = 1.5 \pm 0.6$  determined from the Balmer lines which we assume arise very close to the nucleus compared to the extended emission. This is an extreme reddening which we feel is unlikely to be correct for the extended emission itself, but it is the only value we have based on actual measurements. We can make an estimate of the reddening by comparison with the Galaxy and assuming that the extinction in the Galaxy and in NGC 6251 are equal. We determine  $A_V = 0.6$  in the Galaxy from the work of Burstein and Heiles(1981) and then assume the same value for NGC6251. With a standard extinction law, ths corresponds to  $E(VB - V) = 0.4$ . Without any actual source to determine the reddening, we will use a compromise value of  $E(B - V) = 1.0 \pm 0.6$  for the following discussion. We emphasize that this is a rather uncertain reddening correction. Nevertheless, the basic conclusions are still valid if we use the lower limit of this reddening correction.

Under these assumptions, the extinction correction increases the U-band flux relative to the B-band flux by about 200%. Thus we find  $U - B = -2.2 \pm 0.9$ . This is indeed a rather extreme value.

Taking account of the reddening, its uncertainty and using the fluxes for F342W and F410M given above, we find the intrinsic spectrum of the extension to be  $F_\lambda \propto \lambda^{-5.8 \pm 3.1}$  (for unreconstructed radio astronomers;  $F_\nu \propto \nu^{3.8 \pm 3.1}$ ). We can use our upper limit to the flux at  $\lambda 5550\text{\AA}$  to constrain the exponent in the power law exponent to be  $< -1.8$  because

otherwise there would be too much flux at  $\lambda 5550\text{\AA}$ . Nevertheless, the intrinsic spectrum is likely to be rather blue.

### 3. Results

Several potential explanations for the observations are immediately ruled out by the absence of radio emission outside the very narrow cone defined by the radio jet. In particular, synchrotron emission as seen in the optical counterparts to radio jets(Crane *et al.*,1993b) is ruled out as well as inverse Compton scattering from hot electrons and Thompson scattering from an ionized gas.

We do not favor emission lines as the origin of the extension. First because the bandpass of the F410M filter contains none of the normal strong emission lines, and yet the extension is clearly detected in this band( see Fig. 4) with a flux close to what is seen in the F342W image. Second, the F555W image includes both the  $H\beta$  and OIII lines. Most scenarios for line excitation would produce more flux in the F555W filter than in the F410M filter. This is not the case so it seems unlikely that the origin is emission lines.

Another potential origin might be thermal radiation from a population of extremely hot stars such as cause the UV upturn seen in many galaxies. The lower limit on  $U - B$  color could be appropriate for a collection of bright early type stars. Thus based on the color and total intensity we determine from our existing data, we cannot rule out the possibility of bright stars as the origin of the extended emission. However, we feel it is not very plausible especially given the implied weakness of the emission lines.

We consider the most promising explanation to be scattering of radiation from a continuum source off the dust ring itself or off material interior to the dust ring. We favor this hypothesis inspite of the low of polarization in the extended region. The high

polarization seen close to the nucleus in Fig. 3 is a major motivation for this interpretation. This polarization is an unambiguous indication that UV light close to the nucleus is scattered light. The maximum of the polarized intensity is concentrated near the radio axis. Although not obvious in Fig. 3, there are a few clumps close to the nucleus that show polarizations close to 50%. Since we believe the radiation both close to the nucleus and in the extension have a similar origin, we postulate the observed radiation in the extension is also scattered. The observed fractional polarization in the extension is reduced by roughly a factor of two from the true fractional polarization by dilution from the foreground emission in the galaxy itself. Thus the extended region may have an intrinsic polarization of 10%.

The main problem with the scattering hypothesis is that the usual scenarios for radiation emanating from galactic nuclei have the radiation confined to a cone along the axis of the radio emission. The region in the plane perpendicular to the radio axis is presumably obscured by a torus of material surrounding the active nucleus. In this case it appears that this obscuration is either not present, or if it is, then we are seeing radiation that has been scattered away from the radio axis, and is now scattered a second time towards us. This double scattering may be the origin of the extremely blue spectrum. If the scattering hypothesis turns out to be correct, then these observations do not fit easily into standard geometries of active regions.

We should emphasize that none of the proposed scenarios is entirely satisfactory, nor are any definitively ruled out except perhaps the non-thermal radiation processes which would give rise to radio emission. This is a particularly frustrating state of affairs.

#### 4. Discussion

The canonical models of the nuclear activity in galaxies typically involve high energy radiation which is possibly beamed, and interacts with confining material. The geometry and composition of the confining material and the viewing angle of the observer are then supposed to determine most of the observed properties. Observations with the HST have provided us with several good examples which tend to confirm this model. Notable among these are the galaxies NGC 1068 and NGC 4261.

The early HST observations of NGC 4261(Jaffe, *et al.*,1993) revealed a disk of dust surrounding the bright nucleus. Subsequent HST observations(Jaffe, *et al.*,1996, Farrarese, Ford, and Jaffe, 1996) have confirmed and extended these early results. Except for the extended U-band emission, the dust features seen in the images of NGC 6251 are quite similar to those seen in NGC4261. The sizes are similar; 240 pc for NGC 4261 and 280 for NGC 6251. The orientations to the line of sight are also similar;  $64^\circ$  and  $68^\circ$  respectively. The misalignments of the axes of the dust features relative to the radio jet axes are also similar. These facts suggest a strong similarity in the origin of the absorbing dust features seen in these sources. However, this does not help to explain the U-band emission seen in NGC6251. The major difference between these sources is that the nuclear source on NGC6251 is several times brighter than that of NGC4261.

Since the extended emission is very faint and close to a bright point source, it will be difficult to obtain further data that could provide the clues needed to explain what we have found here. Clearly FOC images in other filters can provide some of the data we would require. With modern ground based telescopes, under excellent seeing conditions, and with appropriate spatial sampling, it should also be possible to get a reasonable spectrum of the extension by making use of our knowledge of the spatial distribution obtained with HST.

Perhaps even more promising than further study of this source, would be observations of other promising candidates with the FOC UV filters. Prominent among these candidates

would clearly be NGC4261, but we can easily imagine several others. One point which we would like to emphasize in this regard is the almost entire lack of good high resolution UV images of nearby galaxies in the HST program. Our experience has shown that this is an extremely rewarding if not perplexing avenue to pursue.

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Table 1: Observational Data

Camera	Filters	Exp Time	Date	Sequence
FOC F/96	F342W	1196	19 Feb 96	x33t0301
FOC F/96	F410M	1315	19 Feb 96	x33t0302
FOC F/96	F342W/POL0	2931	6 Jun 96	x37y0301
FOC F/96	F342W/POL0	3222	6 Jun 96	x37y0302
FOC F/96	F342W/POL60	3176	6 Jun 96	x37y0303
FOC F/96	F342W/POL60	3222	6 Jun 96	x37y0304
FOC F/96	F342W/POL120	3176	6 Jun 96	x37y0305
FOC F/96	F342W/POL120	3222	6 Jun 96	x37y0306
PC2	F555W	400	28 Jun 95	u2pq0701
PC2	F555W	400	28 Jun 95	u2pq0703
PC2	F814W	260	28 Jun 95	u2pq0704
PC2	F814W	260	28 Jun 95	u2pq0705
PC2	F814W	200	28 Jun 95	u2pq0706

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O'Neil,E.J, and Lynds,R. DeYoung,D.S,*et al.*,1994, BAAS,184,4905.

Perley,R.A., Bridle, A.H., and Willis, A.G., 1984 ApJS,54,291.

Shuder,J.M. and Osterbrock,D.E.,1981,ApJ,250,55.

Thomson, R., Crane, P., and MacKay,C. 1995, ApJ,446,L93.

Vernet, J.,and Crane, P.,1997 in preparation.

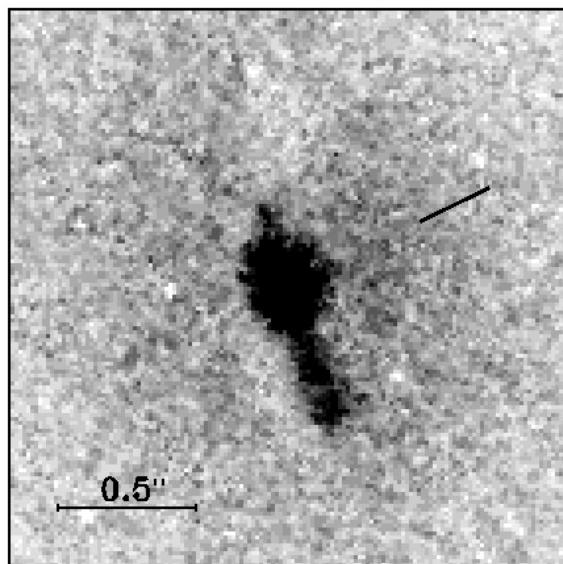
Fig. 1.— The upper left panel shows the FOC F342W total intensity image obtained from the polarization data. The upper right panel shows the FOC F401M image, while the lower images are the sums of the PC2 F555W(left) and F814W(right) images. These images have been scaled to the same resolution. Each panel covers an area of 2.0 arcsec square. The axis of the radio-jet is indicated in the upper left panel. It lies at a position angle of  $300^\circ$  whereas the axis of the extended emission is at position angle of  $\approx 200^\circ$ .

Fig. 2.— Greyscale image of the U band image. The dark contours are determined from the U-band image. The white contours have been selected from the V-band image to emphasize the dust ring.

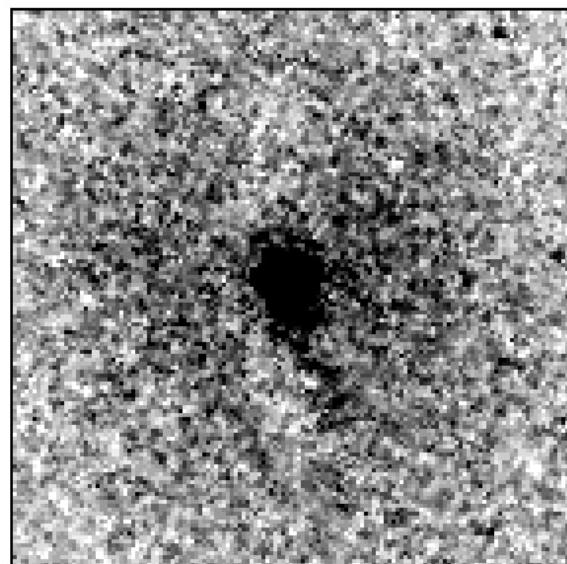
Fig. 3.— The greyscale shows the total intensity image averaged over  $4 \times 4$  pixels to give a resolution of 0.056 arcsec. The arrows show the direction and magnitude of the polarization. Note that the only regions of high polarization are symmetrically placed near the nucleus.

Fig. 4.— Intensity profiles along the extension for each bandpass.

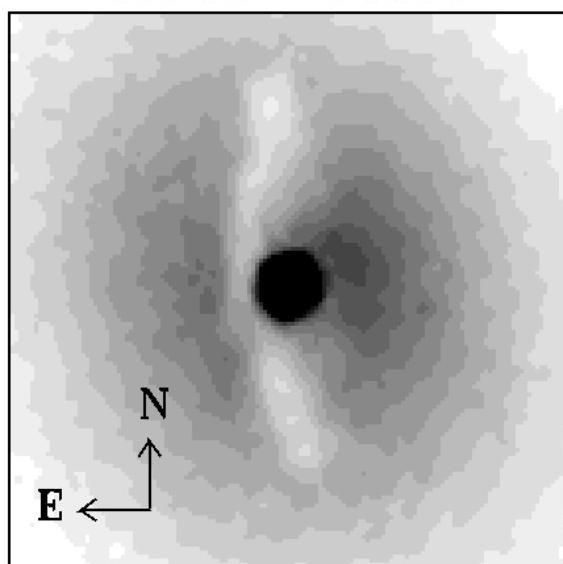
FOC – F342W



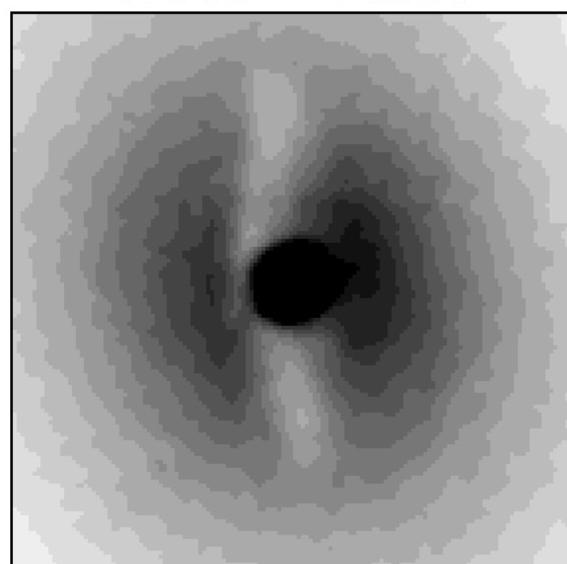
FOC – F410M

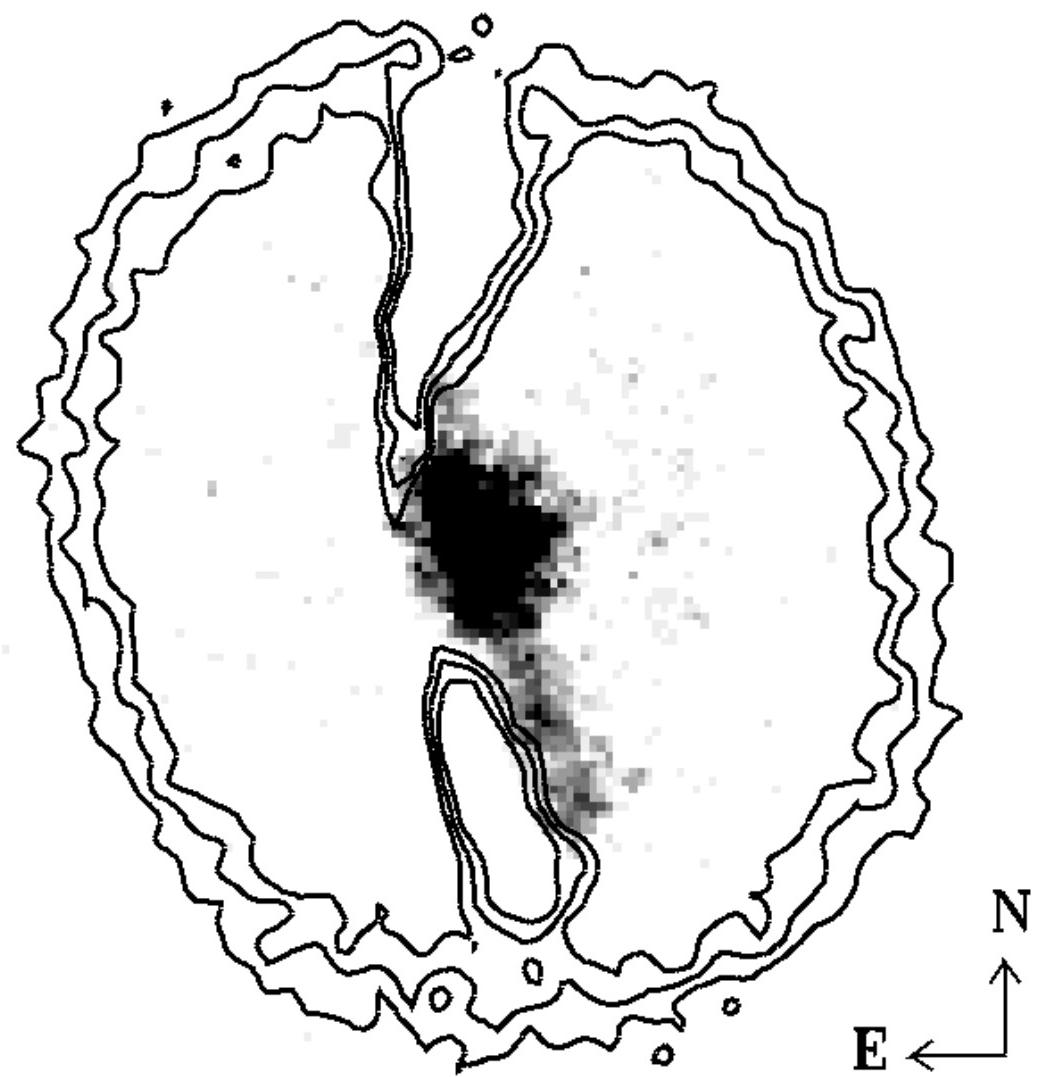


WFPC2 – F555W



WFPC2 – F814W





NGC6251 – Polarization Map – F342W

